Buckling Failure of Compressed Cellular Members

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Summary

Structural cellular members are more economical in material use than plain-webbed members because of the large openings present in their web. Consequently, these members are mostly used for applications in which they are primarily loaded in bending, but they are also used for applications in which they are loaded by an axial compressive force combined with a relatively large bending moment. In the latter loading condition, the behaviour of cellular members is still unknown and is currently being investigated. As a part of this more extensive research, the authors studied the failure behaviour of simply supported, doubly symmetric cellular members loaded by an axial compressive force and proposed a design approach to calculate the ultimate failure load. In this paper, the results of a preliminary study are presented, which demonstrates that the proposed design approach could lead to acceptable results, depending on the effect of the residual stresses.

Keywords: *cellular members, flexural buckling, Abaqus, numerical simulations, columns*

1. Introduction

Cellular members are steel members with an I-shaped cross-section, of which the web contains large round web openings (*Fig. 1*). Castellated members are similar, but have hexagonal instead of circular web openings. The main advantage of these beams is their increased resistance in bending: for the same amount of steel, these beams can span larger distances than regular I-section beams, because of the increased height of their cross-section. Using these beams, it is possible to make structures which are lighter in weight and appearance. Logically, these beams are mainly used for applications in which they are only subjected to a bending moment about the strong axis. As a consequence, almost all research about the influence of the web openings on the failure of these beams has focused on this loading condition. A good overview of the different failure mechanisms of castellated beams in ambient conditions was given by Kerdal in 1984 [1], but research concerning the different aspects of the failure behaviour in ambient and fire conditions is still going on.

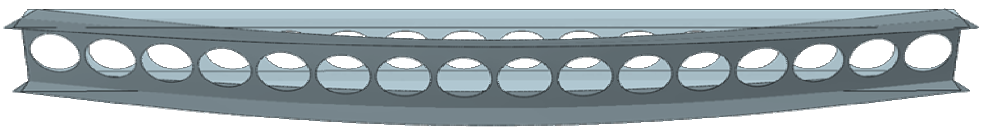

Fig. 1: Flexural weak-axis buckling of a cellular member

A cellular member can be used as well for applications in which it is subjected to an axial force and a large bending moment. In the same way as for beams loaded in pure bending, the presence of the openings will alter the failure behaviour of cellular members in this loading condition. However, according to the authors' best knowledge, no research on this topic is available. Consequently, this topic is currently being investigated by the authors. As a part of this more extensive research, the general buckling behaviour of simply supported cellular members loaded by a compressive axial force has been studied. Even for this limiting case, research is almost nonexistent. The strong-axis buckling behaviour of cellular and castellated members was studied respectively by Sweedan et al.

[2] and El-Sawy et al. [3]. However, because it is expected that axially loaded simply supported cellular members will fail by weak-axis flexural buckling (*Fig. 1*), our focus is on flexural buckling about the weak axis of the cross-section. Currently, a design rule to calculate the failure load of these members is lacking.

To develop a design rule for this loading case, the authors have made numerical simulations with the finite element package Abaqus for a number of realistic cellular member geometries. Geometrical imperfections, as well as material and geometrical nonlinearities, were taken into account to determine the failure load of the cellular members. In these simulations, residual stresses were not taken into account explicitly, but their effect was estimated by considering the results from numerical simulations for plain-webbed members. In previous work, the authors have already investigated the elastic buckling behaviour of these members [4]. Using the results of the numerical simulations combined with these previous results, we have developed a design approach to check the buckling resistance that fits in the Eurocode 3 framework [4].

In this paper, the proposed buckling resistance check will be presented. Furthermore, the failure loads obtained using this design approach will be compared with the results from the numerical simulations. In future work, the yet unknown residual stresses in cellular members will be examined and their effect on the buckling failure of cellular members will be determined in larger depth. Ultimately, the more general case of combined bending and compression will be examined in order to formulate a general design rule for cellular members loaded in compression and bending.

2. Proposed design approach

The design approach that is proposed for the weak-axis flexural buckling of compressed cellular members is based on the design rule that exists for the lateral-torsional buckling of cellular members loaded in strong-axis bending. This rule, originally from the European pre-standard ENV3 [6], is further detailed in a European research report [7]. Based on the findings of Nethercot [8], the design rule states that the lateral-torsional buckling moment of cellular beams can be calculated in the same way as for plain-webbed beams, but using the cross-sectional properties calculated at the centre of a web opening instead of the properties of the gross cross-section in all expressions. In [9], the authors investigated if the elastic buckling moment according to the proposed design rule matched with the results of numerical simulations for a very wide variety of cellular member geometries. It was found that the agreement was quite good, but that for some short-length geometries the design rule was slightly unsafe because of web-distortion. However, it was expected that these unsafe anomalies would vanish once plasticity was taken into account, because these specific geometries then would fail by plastic yielding instead of elastic buckling. This was confirmed in later work [10], where the failure load of cellular members was determined numerically.

The authors propose that the same approach as the one used for lateral-torsional buckling of cellular members can be used for the weak-axis flexural buckling of cellular members. We checked this approach for elastic buckling in [4], by comparing the results of the design approach with the results of finite elements simulations for the same wide variety of cellular member geometries as used for elastic lateral-torsional buckling. Overall agreement was found to be very good, but for some short-length geometries, the design rule yielded slightly unsafe results, due to web-distortion. However, it is expected that these unsafe deviations will become irrelevant as well if the effect of steel plasticity is taken into account.

Fig. 2: Member subjected to an axial load N

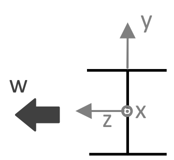

Fig. 3: Cross-section axes and displacement

In the remainder of this section, the proposed design rule for weak-axis flexural buckling of cellular members will be presented. Only simply-supported, doubly symmetric members loaded by an axial compressive force will be considered, as illustrated in Fig. 2. For the considered geometries and in this loading and support condition, the critical buckling mode will be the weak-axis flexural buckling mode, in which the cross-section experiences only lateral displacements w (Fig. 3).

According to the proposed design rule, the critical weak-axis flexural buckling load N_{cr} can be determined using expression (1). In this expression, L is the length of the member and EI_y the weak-axis bending stiffness of the member, calculated at a cross-section at the centre of the web opening. This is the expression that was previously examined by the authors in [4], as mentioned before.

$$N_{cr,y} = \frac{\pi^2 EI_y}{L^2} \quad (1)$$

This critical force N_{cr} will be the failure load for a perfectly straight, elastic member without any imperfections. However, real members display imperfections and residual stresses, as well as nonlinear geometrical and material behaviour. According to the EC3 concept, this leads to the design buckling resistance N_{Rd}, given by expression (2). This expression and the following expressions are only valid for class 1, 2 and 3 cross-sections [5].

$$N_{Rd} = \frac{\chi A f_y}{\gamma_{M1}} \quad (2)$$

In this expression, χ is the weak-axis flexural buckling reduction factor, A is the surface area of the member, f_y the uniaxial yield stress of the steel and γ_{M1} a partial safety factor. The value of γ_{M1} was recently reduced from 1,1 in ENV3 to 1,0 in EC3 for buildings [5],[6] .

The reduction factor χ can be calculated using expressions (3)-(5), in which $\bar{\lambda}$ is the non-dimensional slenderness and α an imperfection factor, depending on the buckling curve, of which the relevant values can be found in *Table 1*. As a preliminary assumption, is it proposed that the relevant buckling curve for cellular members is the same buckling curve as the one that should be used for the parent section according to EC3 [4]. In this way, the effect of the larger initial stresses in the parent section is taken into account.

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \leq 1 \quad (3)$$

$$\phi = 0,5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] \quad (4)$$

$$\bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}} \quad (5)$$

Table 1: imperfection factors for different buckling curves

Buckling curve	a	b	c
Imperfection factor α	0,21	0,34	0,49

The three applicable buckling curves are depicted in *Fig. 4*. In the graph, the non-dimensional slenderness $\bar{\lambda}$ is given on the horizontal axis and the reduction factor χ on the vertical axis. For low values of the slenderness $\bar{\lambda}$, the member will fail by plastic yielding and χ=1. For very slender members, the member will fail by elastic buckling and $\chi_{el}=1/\bar{\lambda}^2$. For each examined geometry, the non-dimensional slenderness $\bar{\lambda}$ and the reduction factor χ can be calculated.

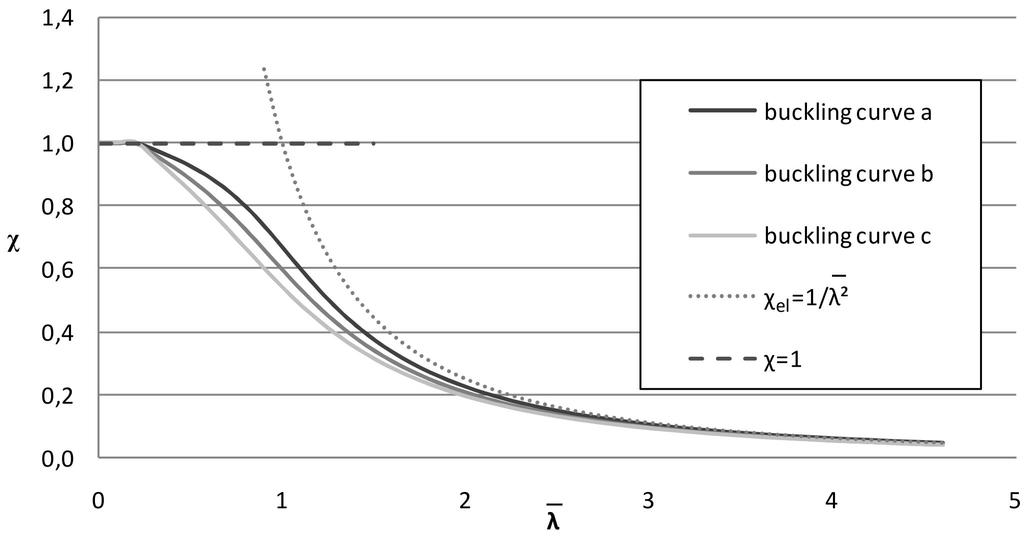

Fig. 4: Buckling curves: reduction factor χ as a function of the non-dimensional slenderness $\bar{\lambda}$

3. Examined geometries

Cellular members are constructed starting from a rolled I-section member, the parent section. The web of this member is cut as depicted in Fig. 5. After this operation, the two obtained T-sections are shifted and welded together. In the current research, only one parent section for each cellular member is considered, but it is also possible to fabricate a cellular member starting from two different parent sections.

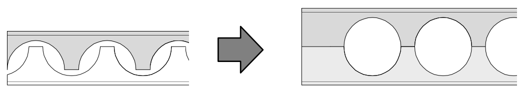

Fig. 5. Fabrication of a cellular member starting from a plain-webbed parent section

In this work, two different parent sections were considered: the European structural shapes IPE300 and HE320A, both of steel grade S235. All realistic doubly symmetric geometries that can be made starting from these parent sections were considered by varying the opening diameter, the width between the openings and the length of the member. These geometries belong to the larger group of cellular member geometries considered by the authors in the elastic flexural buckling research [4], in which the results of finite element simulations in Abaqus were compared with the results of the analytical expression given by (1). For the geometries with the HE320A parent section, the lowest values of $N_{cr,abq}/N_{cr}$ were obtained: for the short length geometries $N_{cr,abq}/N_{cr}$ reached its overall minimum value of 0,97. This small unsafety of the design rule was due to distortion of the cross-section. For the members with the IPE300 parent section, the approximation of the analytical expression was very good, with $N_{cr,abq}/N_{cr}$ varying between 0,99 and 1,00 and no perceivable web-distortion.

All examined cellular member cross-sections have class 2 cross-sections (determined using annex N of ENV3, [6]).The appropriate buckling curves are buckling curve c and b, respectively for the HE320A and the IPE300 parent sections. In the following, some results about the parent section will also be considered briefly. The parent section HE320A has a class 1 cross-section, whereas the IPE300 parent section has a class 2 cross-section.

4. Finite element model

The ultimate failure load of each examined cellular member $N_{Rd,abq}$ was calculated with the finite element package Abaqus. Using the modified Riks method, a geometrically nonlinear analysis was performed, taking into account nonlinear material behaviour and initial geometric imperfections. The obtained failure load $N_{Rd,abq}$ was used to calculate a reduction factor χ_{abq}, which was compared with the reduction factor χ corresponding to (3), in order to determine whether the examined design rule is accurate.

The geometry was simulated in Abaqus using quadratic shell elements with reduced integration (S8R) for both the flanges and the web. The fillet between the flanges and the web was not taken into account. The cellular member was simply supported and the axial compressive force was applied by means of line loads acting on the flanges and the web at the ends of the member.

The material used was steel of grade S235, with a yield stress f_y of 235 MPa. A bilinear stress-strain curve without strain hardening, with a Young's modulus of 210 GPa was implemented. The used Poisson's ratio of the elastic steel was 0.3. An initial lateral geometric imperfection, with a half sine-wave shape and amplitude e_0 at mid-span was introduced in the model. The amplitude of this imperfection was L/1000.

For the cellular members, the residual stresses are expected to be altered by the production process. However, no research results are available about the residual stresses in cellular members. As a first approximation, the residual stresses were not taken into account for the cellular members. As a consequence, the reader has to take this possible additional unsafety into account when examining the results of the numerical simulations. Further experimental and numerical research may be needed to determine the residual stresses in cellular members.

For the plain-webbed parent sections, the effect of residual stresses was investigated numerically, using the same finite element model as for the cellular member. For each examined member, the failure load was calculated twice: once taking into account residual stresses, and once not considering residual stresses. In this way, we obtained an estimate of the possible effect of residual stresses on the buckling load. The used residual stress pattern was the conservative pattern proposed by the ECCS in [11], as depicted in *Fig. 6* (in this figure, compressive stresses are negative).

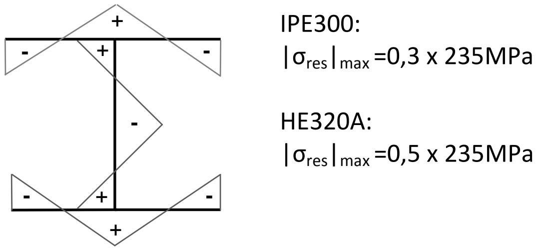

Fig. 6: Residual stress pattern for hot-rolled members (ECCS)

5. Comparison of results and discussion

For each examined geometry, two values were determined. Firstly, the non-dimensional slenderness $\bar{\lambda}$ was determined using expressions (1) and (5). Secondly, χ_{abq} was determined by substituting N_{Rd} by $N_{Rd,abq}$ in (2) and solving the expression to find χ. In order to compare the numerical simulations with the design rules, these values were plotted in the same graph as the buckling curves, as depicted in *Fig. 7*.

According to the proposed design rule, buckling curve b should be used for the cellular members with a IPE300 parent section, and buckling curve c for the cellular members with a HE320A parent section. In *Table 2*, the maximum and minimum values of χ/χ_{abq} are listed. For the cellular members with larger values of the slenderness $\bar{\lambda}$, the numerical results approach the values obtained using the design rule: the maximum values of χ/χ_{abq} correspond with these values of $\bar{\lambda}$. The results of the design rule and the results of the numerical simulations are the most distinct for the values of $\bar{\lambda}$ around unity: the minimum values of χ/χ_{abq} correspond with these values of $\bar{\lambda}$. Overall, a seemingly large safety of the design rule can be seen. However, it should be emphasised that the detrimental effect of the residual stresses on the flexural buckling behaviour of these members was not considered. Because of this, an additional, yet unknown, safety factor has to be taken into account.

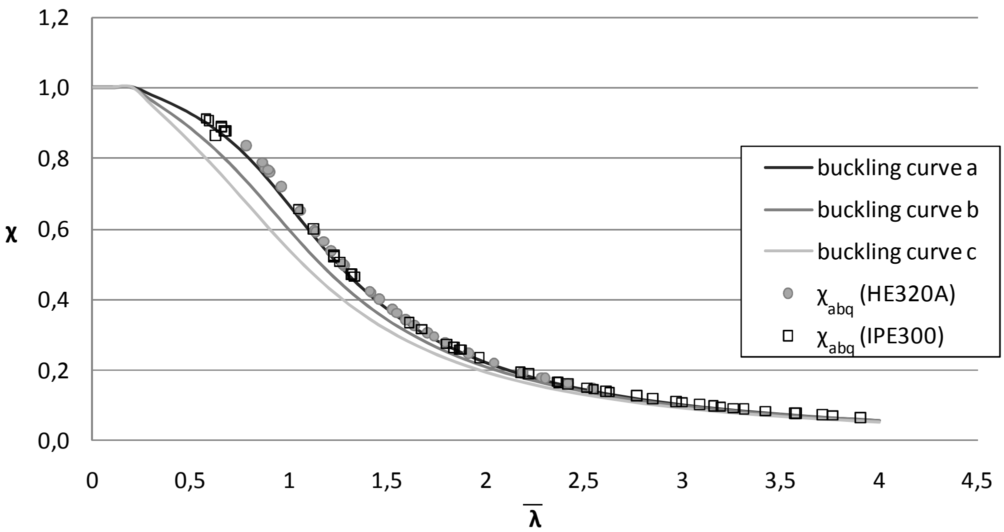

Fig. 7: Comparison of the results of numerical simulations and the design rule for cellular members

Table 2: Comparison of design rule with results of numerical simulations for cellular members

	HE320A	IPE300
Maximum χ/χ_{abq}	0,87	0,93
Minimum χ/χ_{abq}	0,72	0,87

The effect of residual stresses on the flexural buckling behaviour is illustrated for the two plain-webbed parent sections of the cellular member. For each parent section, six different lengths were considered. For each of these lengths, the ultimate failure load is calculated numerically: once without residual stresses and once with residual stresses (according to Fig. 6). The results for each finite element simulation are depicted in Fig. 8 and Table 3. The results for the HE320A section should match with buckling curve c, while the results for the IPE300 section should match with buckling curve b.

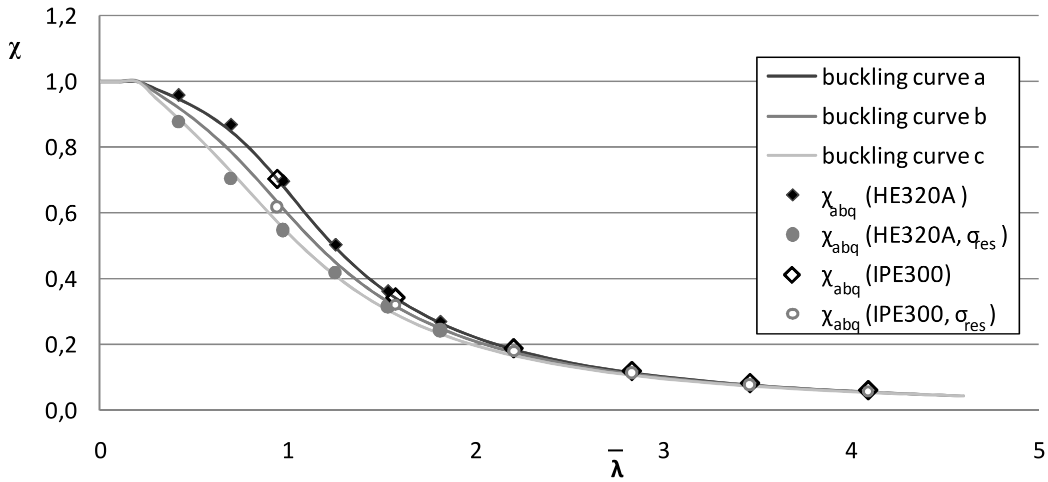

Fig. 8: Comparison of the results of numerical simulations and the design rule for the parent sections

The decrease of the failure load in the numerical simulations caused by the residual stresses can be seen in *Table 4*. For the plain-webbed members, it can be seen that, without residual stresses, the numerical results lie closely to buckling curve a. If the residual stresses are taken into account, the numerical results for the HE320A member suffer a decrease of up to 21%. For the IPE300 cross-section members, for which the residual stresses are less pronounced, the decrease is less severe: up to 12%. The detrimental effect of the residual stresses is more pronounced for the examined geometries with values of the slenderness around unity. This complies with what is expected theoretically: if the slenderness increases, the buckling behaviour of the member approaches the elastic buckling behaviour and the residual stresses will have less influence. For very short members or small slenderness values, the member will fail by plastic yielding. In the latter case, the effect of the residual stresses will be non-existent. As a result, the detrimental effect of the residual stresses is the highest for members with intermediate values of the slenderness.

Table 3: Comparison of results of numerical simulations with design rule for the parent sections

	HE320A	HE320A + σ_{res}	IPE300	IPE300 + σ_{res}
Minimum χ_{abq}/χ	1,08	0,97	1,07	0,98
Maximum χ_{abq}/χ	1,26	1,06	1,11	1,06

Table 4: Effect of residual stresses on the ultimate failure load

	HE320A	IPE300
Minimum $N_{abq,\sigma res}/N_{abq}$	0,79	0,88
Maximum $N_{abq,\sigma res}/N_{abq}$	0,92	0,98

The detrimental effect of the residual stresses on the buckling load of the plain-webbed parent sections can be used as a preliminary estimate of the effect of residual stresses on the failure load of the cellular members. This effect is the largest for the values of the slenderness for which the safety of the proposed design approach was the highest. As a result, the estimated detrimental effect of the residual stresses is always slightly smaller than the additional safety that is present in the design rule for the flexural buckling of cellular members. As a result, it is very well possible that the design rule that was proposed in this paper gives acceptable results for cellular members with residual stresses. However, to be fully certain, numerical simulations in which the residual stresses of cellular members are considered will have to be executed. Before this is possible, a conservative residual stress distribution for cellular members will have to be determined by studying the effect of the production process of cellular members on the residual stresses. However, it is also possible that the effect of the production process on the residual stresses and consequently on the flexural buckling failure of the members is considerably detrimental. If this is the case, adapted buckling curves will be needed.

6. Conclusions

In this paper, a design rule which can be used to calculate the ultimate failure load of simply supported cellular members loaded by an axial compressive force is proposed. According to this rule, the ultimate weak-axis flexural buckling load can be calculated using the same approach as described in EC3 for plain-webbed members, but with all cross-sectional properties calculated at the centre of a web opening. It was assumed that the relevant buckling curve is the same as the buckling curve used for the original parent section.

The proposed design rule was examined by comparing the results from this rule with the results from finite element simulations in Abaqus. The array of considered geometries was found by determining all feasible geometries from the HE320A and IPE300 parent sections. Material and geometric nonlinearities, as well as geometric imperfections were taken into account in the numerical simulations. By lack of available results for cellular members, residual stresses were not taken into account. As a result of this, the failure load obtained in the simulations will be higher than the true failure load of members with considerable residual stresses. The effect of the residual stresses was determined for the two plain-webbed parent sections, for which conservative residual stress patterns have been determined in the past. In this way, the possible effect of the residual stresses on the failure of the cellular members could be estimated.

As expected, the numerical failure load for weak-axis flexural buckling is considerably higher than the design failure load for all examined cellular member geometries. The detrimental effect of the residual stresses on the flexural buckling of plain-webbed members is slightly smaller than the overestimation of the ultimate failure load for cellular members by the design rule. As a result, it is very well possible that the proposed design rule might still give safe and acceptable results if residual stresses are taken into account in the numerical simulations. However to be fully certain, a (conservative) residual stress pattern for cellular members will have to be determined by considering the possible effects of the production process of cellular members. Using this residual stress pattern, the numerical simulations can be repeated and the influence of the residual stresses on the ultimate flexural buckling failure load of cellular members can be determined. This will be done in future research for this loading condition, as well as all possible combinations of strong-axis bending and compression.

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